Feasibility study of the rare decay $D^0 \to \gamma\gamma$ & $D^0 \to \mu^+\mu^-$

full & fast MC simulation @ PANDA

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Motivation

- In Standard Model (SM), Flavor Changing Neutral Currents (FCNC) are forbidden at tree level and highly suppressed by GIM mechanism at loop level

- Search for the decay of $c \rightarrow u\gamma$ transition which has a sign of beyond SM
  If not seen, we can contribute to put constraints on new physics parameters

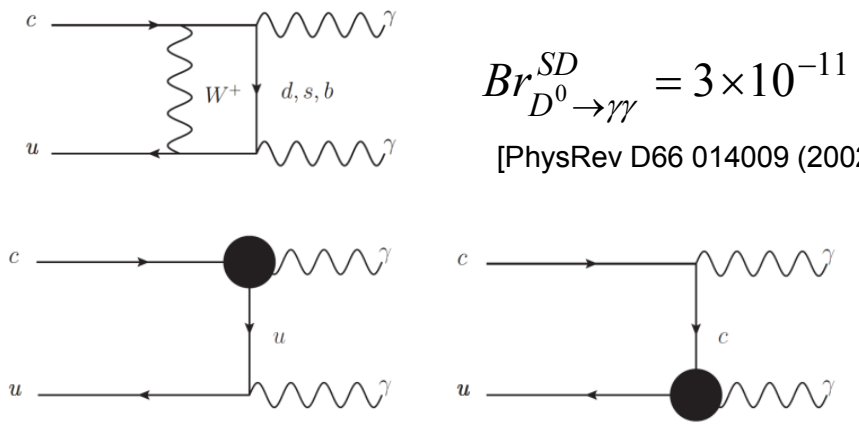
- FCNC rare decay $D^0 \rightarrow \gamma\gamma$ could be an opportunity to pursue with PANDA because electroweak channel involved photons allow a competition with LHCb

Sensitivity accessible @ PANDA?

Branching fraction

Branching fraction of rare decay $D^0 \to \gamma\gamma$

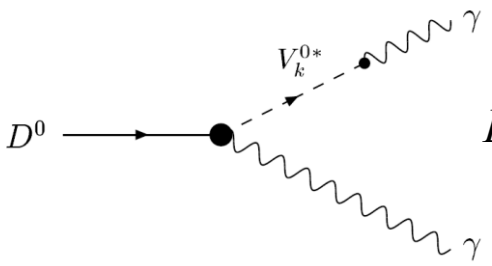
Short distance contribution



$$Br^{SD}_{D^0\to\gamma\gamma} = 3\times10^{-11}$$

[PhysRev D66 014009 (2002)]

Long distance contribution

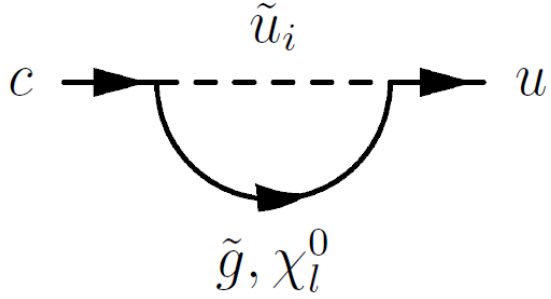


$$Br^{VMD}_{D^0\to\gamma\gamma} = (3.5^{+4.0}_{-2.6})\times10^{-8}$$

[PhysRev D66 014009 (2002)]

New Physics

c→uγ transition can be enhanced by NP, e.g. some NP models can allow at sizeable levels



$$Br^{MSSM}_{D^0\to\gamma\gamma} = 6\times10^{-6}$$

[Phys.Lett.B500 304-312 (2001)]

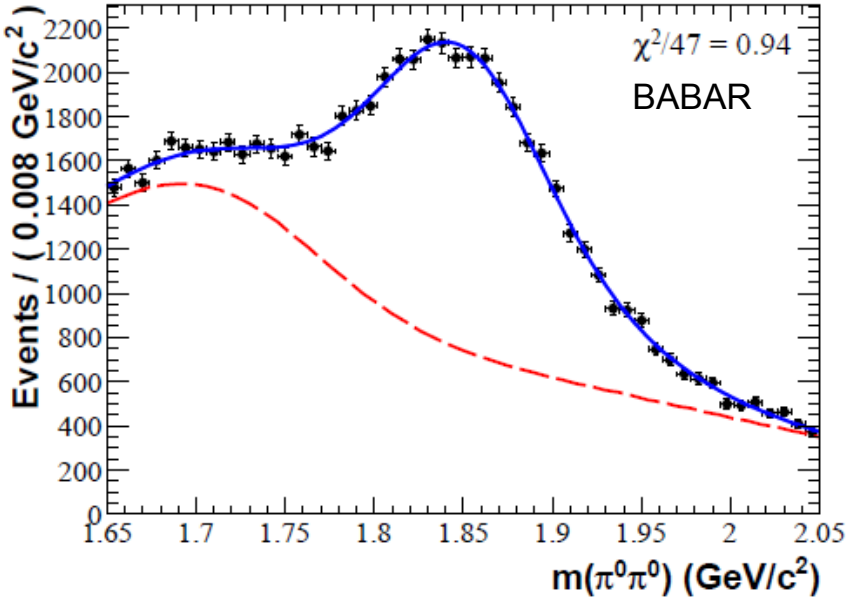
$$Br^{SM,HQ\chi PT}_{D^0\to\gamma\gamma} = (1.0\pm0.5)\times10^{-8}$$

[PhysRev D64 074008 (2001)]

Experimental result

Experimental results (upper limit @ CL=90%)

BABAR	:	$BR < 2.2 \times 10^{-6}$
BESIII	:	$BR < 4.6 \times 10^{-6}$
CLEOc	:	$BR < 8.63 \times 10^{-6}$



BABAR [Phys. Rev. D 85, 091107(R) (2012)]

- Measured $D^0 \to \pi^0\pi^0$ braching fraction :

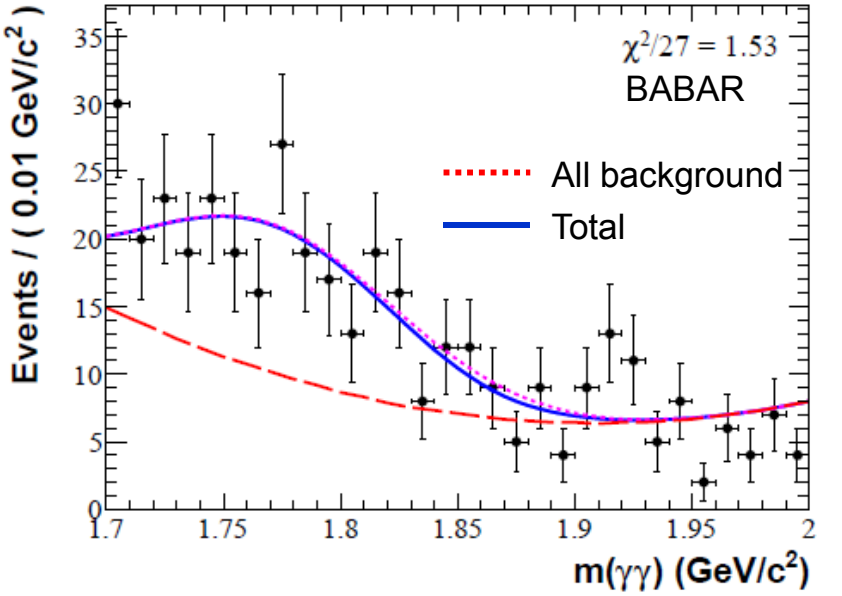
$$Br_{D^0\to\pi^0\pi^0} = (8.4 \pm 0.1 \pm 0.3) \times 10^{-4}$$

- $D^0 \to \gamma\gamma$ found signal yield N = –6±15 events leading to an upper limit :

$$Br_{D^0\to\gamma\gamma} < 2.2 \times 10^{-6}$$

with using the associated(reference) $D^0 \to K_s\pi^0$ decay

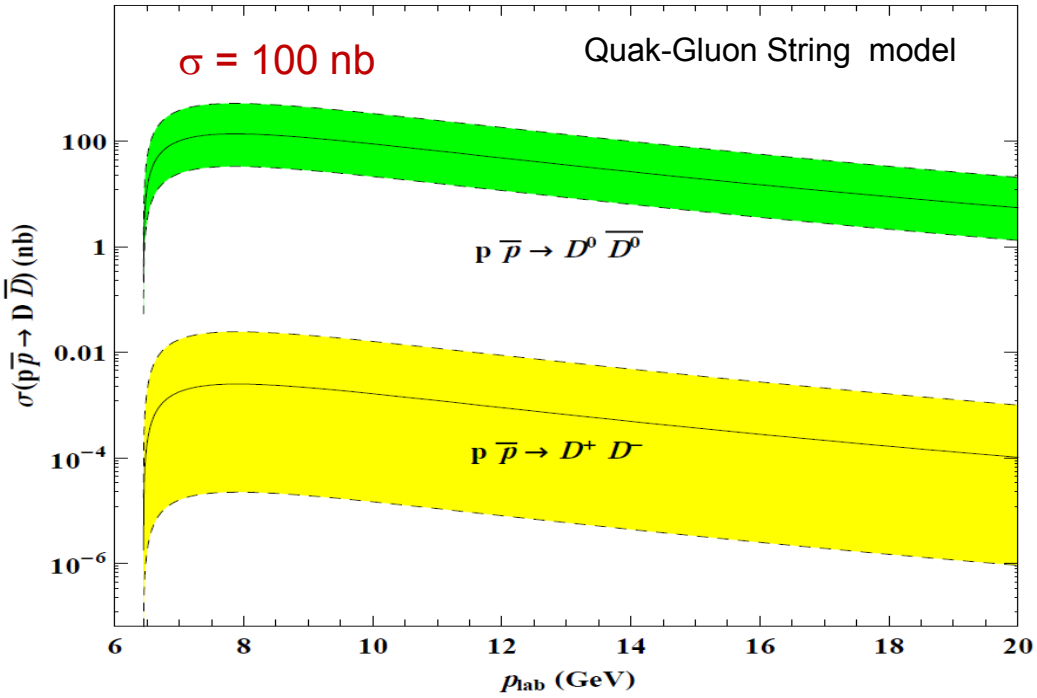
- Constraint NP to at most 70 times SM



Open Charm Cross section

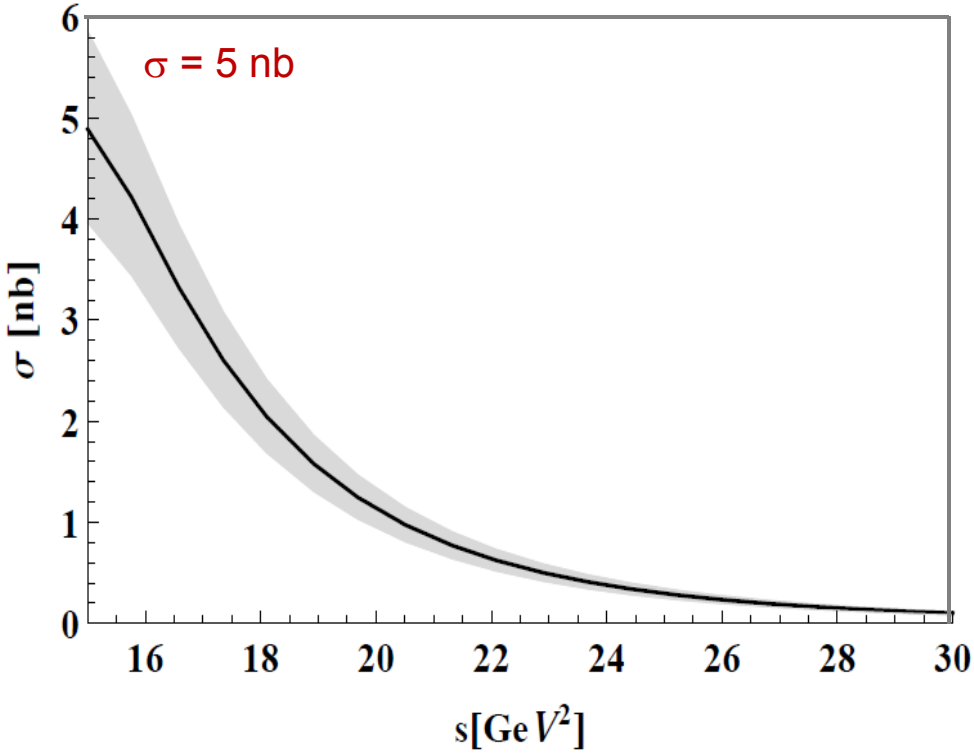
How much charm can PANDA produce?
A.Khodjamirian, Ch.Klein, Th.Mannel and Y.M. Wang

Eur.Phys.J.A 48 (2012) 31.



D^0bar D^0 production at pbarp collisions within a double handbag approach, A.T.Goritschnig, B.Pire and W.Schwieger

Phys.Rev.D87 (2013) 014017



BESIII suggested two different solution for $D^0\overline{D}^0$ cross section using the obtained cross section of $\psi(3770) \to pbarp$, the cross section of $pbarp \to \psi(3770)$ at PANDA is estimated to be

[arXiv:1403.6011v1 24 Mar 2014]

either σ=(9.8±5.7) nb or σ=(425.6±42.9) nb

Expected S/B

High Luminosity : $L = 2\times10^{32}\,\mathrm{cm^{-2}s^{-1}},\quad t = 120\,\mathrm{days\,(year)}$

Expected N : $N = L_{\mathrm{int}}\times\sigma\times\varepsilon\ \ @\sqrt{s} = 3.770(\mathrm{GeV/c^2})$

Number of signal event

$$N_{D\to\gamma\gamma} = 2\,\mathrm{fb^{-1}}\times 100\,\mathrm{nb}\times\varepsilon_S\times Br$$
$$\leq 440\times\varepsilon_S$$

Number of background event

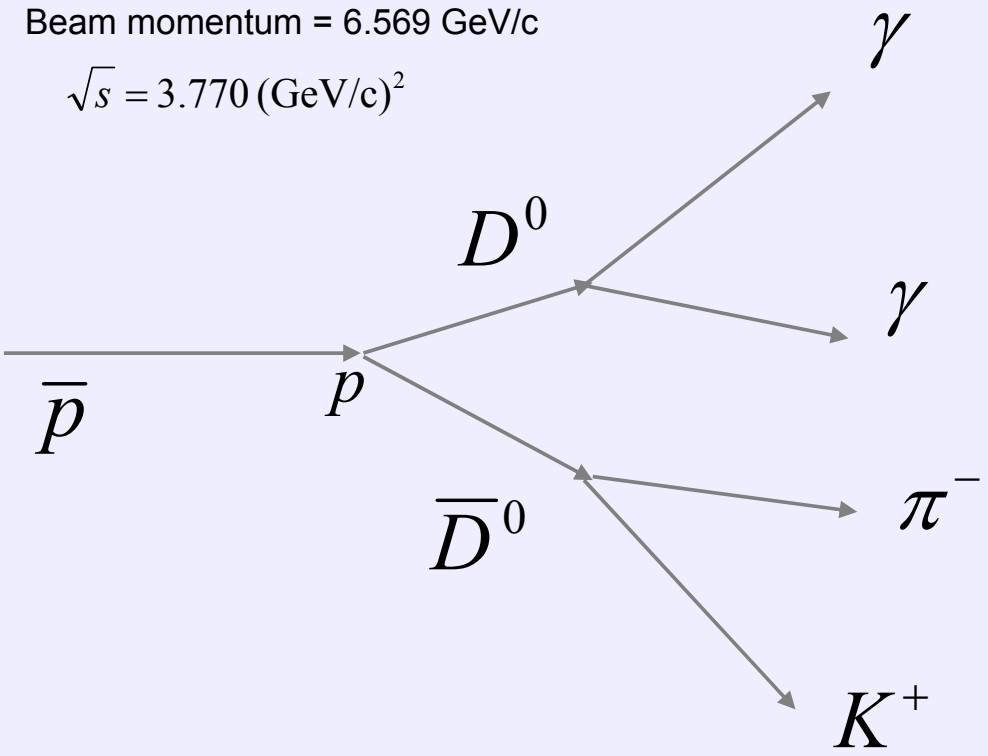
$$N_B = 2\mathrm{fb^{-1}}\times 60\mathrm{mb}\times\varepsilon_B$$
$$= 1.2\times10^{14}\times\varepsilon_B$$

with $Br(D^0\to\gamma\gamma) < 2.2\times10^{-6}$

$$\frac{N_s}{N_B} = 0.01\sim 1 \Rightarrow \text{Background reduction} = \mathbf{10^{-9}\sim 10^{-11}}$$

MC simulation

$$\bar{p}p \to D^0\bar{D}^0 \to \gamma\gamma\, K^+\pi^-$$



- PANDAroot scrut14 release

- Signal EvtGen
  Background $D^0 \to \pi^0\pi^0$ EvtGen
  Background DPM

- Pre-selection of track candidates
  Neutral track : E > 50 MeV
  Charged track : p > 100 MeV/c

$\bar{p}p \to \psi(3770) \to D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-$: quantum number fixed $J^{PC} = 1^{--}$

$\bar{p}p \to D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-$: all possible quantum number (6 states)

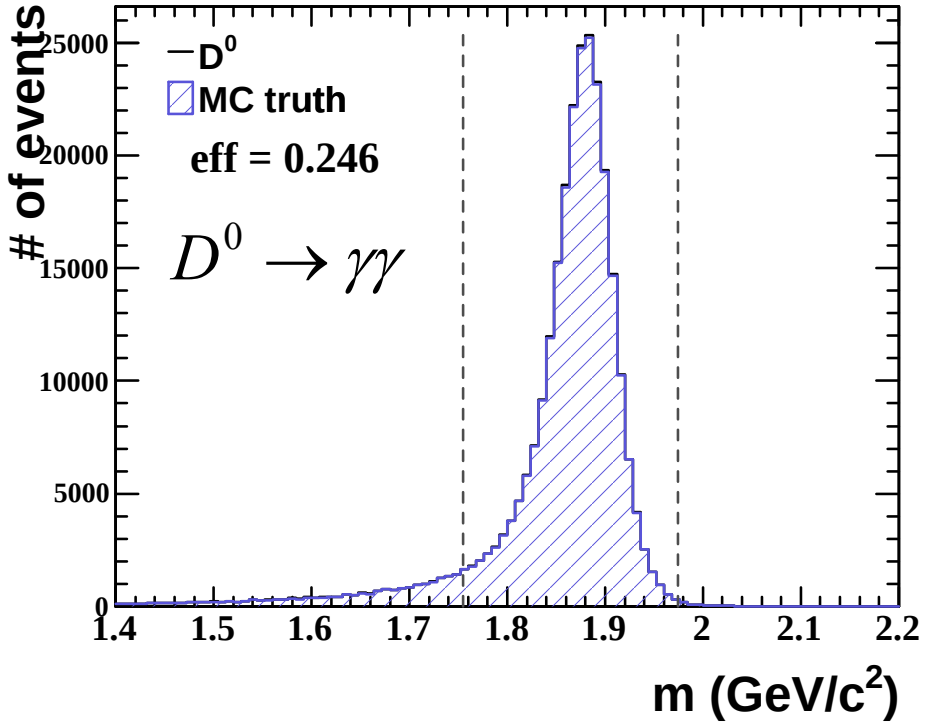
Event selection

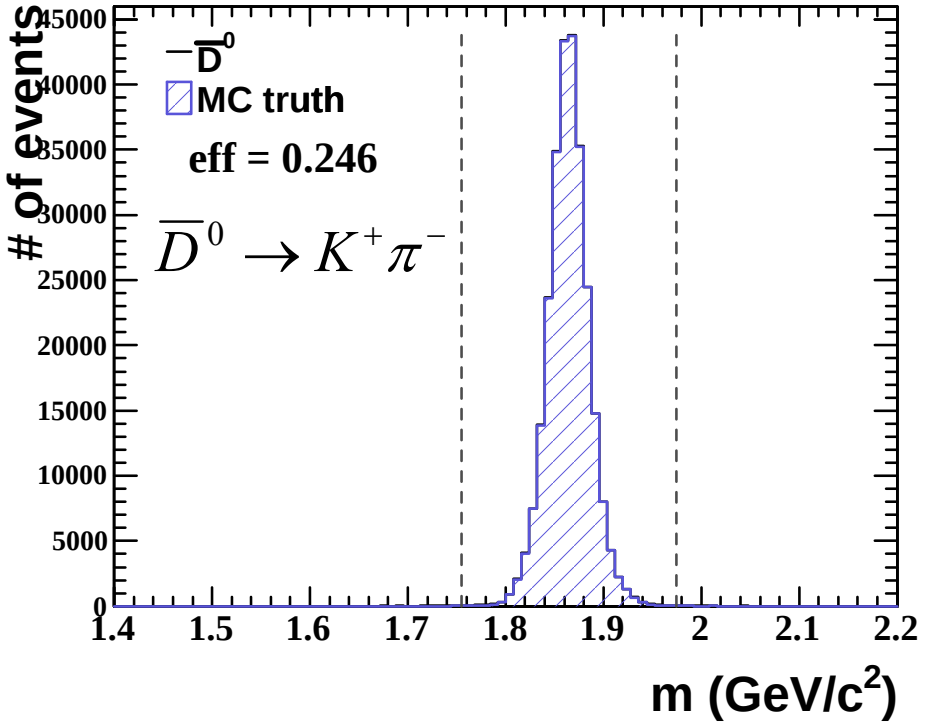
$D^0 \to \gamma\gamma$	$\overline{D}^0 \to K^+\pi^-$
$P_t(\gamma) > 0.1 GeV/c^2$	$P_t(\pi,K) > 0.1$ GeV/c^2
$P_t(D) < P_{t,max} + 0.2 GeV/c^2$	$P_t(D) < P_{t,max} + 0.2$ GeV/c^2
$100° < \Delta\phi_{\gamma\gamma} < 260°$	$100° < \Delta\phi_{\pi K} < 260°$
π^0 veto	PID Prob(π,K) > 0.25
# of ECAL crystal < 36	-
Mass constrain : $0 < \chi^2 < 0.1$	Mass constrain : $0 < \chi^2 < 10$

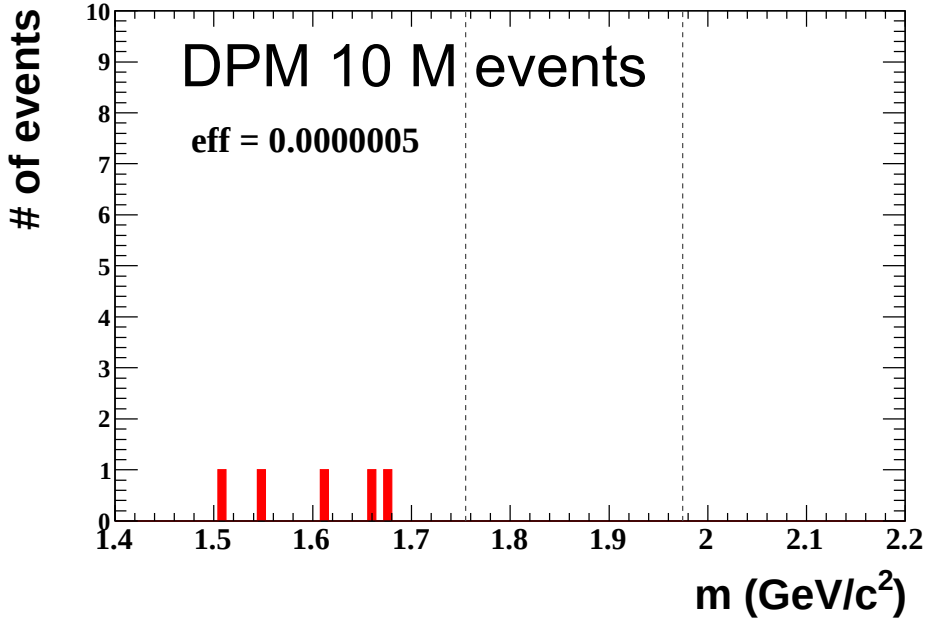
$$\overline{p}p \to D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-$$

$130° < \Delta\phi_{DD} < 230°$
$-0.99 < \cos\theta_{CM} < 0.99$
Mass constrain : $0 < \chi^2 < 0.1$
Mass constrain : $0.8 \leq$ Prob ≤ 1.0

Signal vs Background







$$\varepsilon = \frac{N_{rec.event,MC}}{N_{gen.event,MC}} \text{ in the histogram}$$

Signal efficiency (double tag)

$$\varepsilon_{tag}^{sig} = 0.246$$

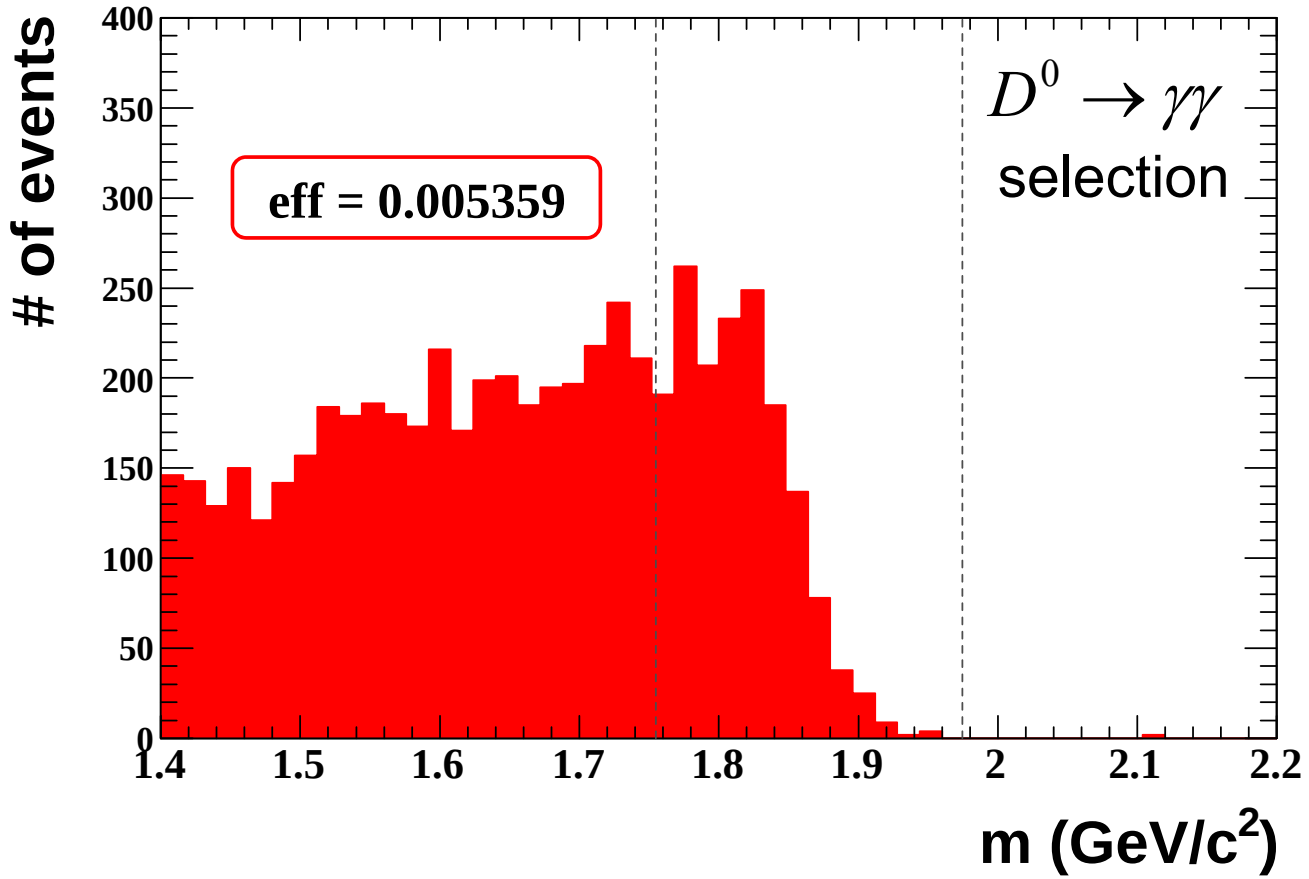
Background efficiency

$$\varepsilon_{tag}^{back} = 5 \times 10^{-7}$$

Test of background reduction I

- DPM background can be manageable up to 10^7 in the full simulation
- Main background source : $D^0 \to \pi^0\pi^0 (Br = 8.4\times10^{-4})$

EvtGen : $\bar{p}p \to D^0\bar{D}^0 \to \pi^0\pi^0\ K^+\pi^-$



Test of background reduction II

1.2×10^{11} DPM inelastic events in the fast simulation

All cuts	**Signal efficiency**	**Background reduction**
+ PID prob > 0.25	0.316	**1.51×10^{-8}**
+ PID prob > 0.50	0.189	**2.20×10^{-9}**
+ PID prob > 0.70	0.163	**7.36×10^{-10}**
+ PID prob > 0.90	0.127	**1.92×10^{-10}**

*elastic contributions are scaled

- Tuned Tracking, EMC, PID detector parameters and used split off
- Background reduction should be possible up to level of 10^{-9} @ fast simulation
- Inelastic event 73% = 43.8 mb & Elastic event 27% = 16.2 mb

Expected number @ PANDA

$D^0 \to \gamma\gamma$ signal data

$$N_{D\to\gamma\gamma} = 2\,\text{fb}^{-1} \times 100\,\text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

$$= 8.4 \text{ events}$$

$$Br(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$$

$$Br(\overline{D}^0 \to K^+\pi^-) = 0.0389$$

$$\varepsilon_{tag} = \varepsilon_{D^0\to\gamma\gamma \,\&\, \overline{D}^0 \to K^+\pi^-} = 0.246$$

$D^0 \to \pi^0\pi^0$ background data

$$N_{D\to\pi^0\pi^0} = 2\,\text{fb}^{-1} \times 100\,\text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

$$= 70 \text{ events}$$

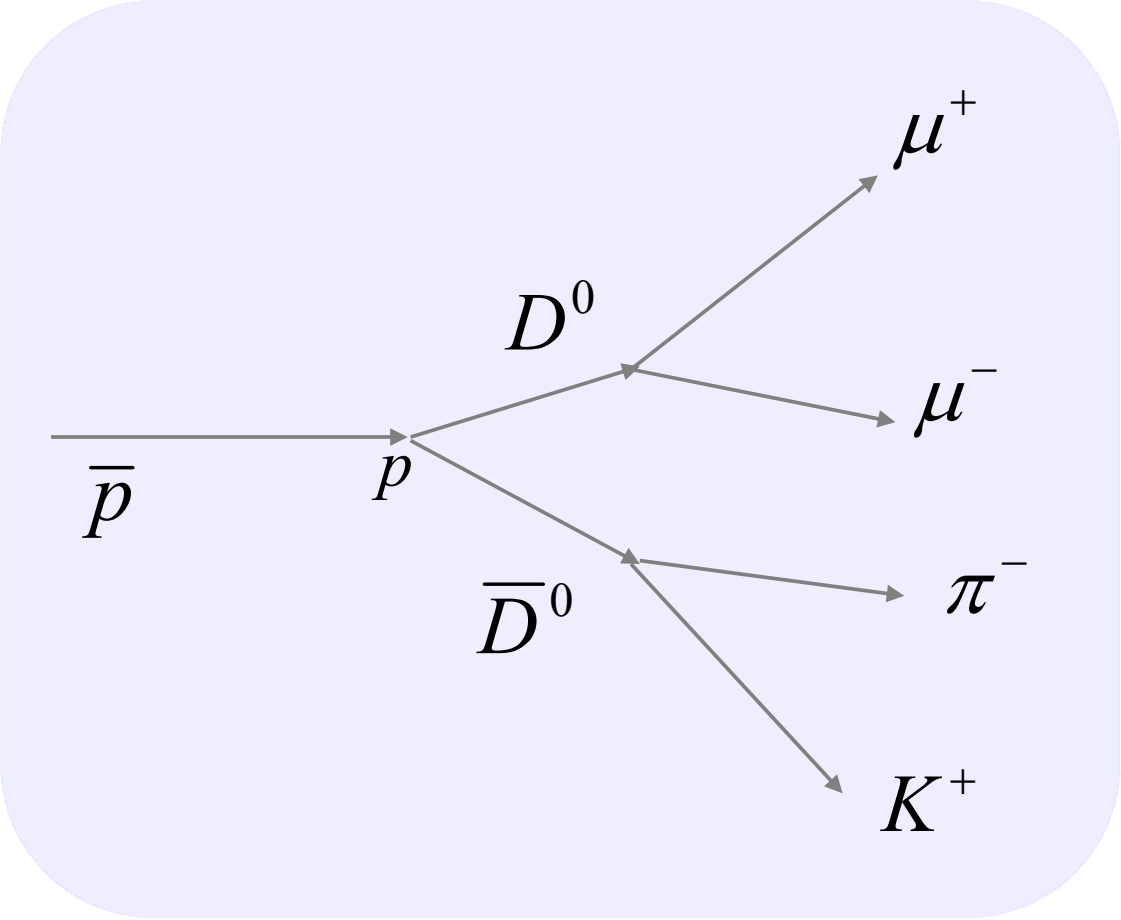
$$Br(D^0 \to \pi^0\pi^0) = 8.4 \times 10^{-4} \text{[BABAR(2012)]}$$

$$Br(\overline{D}^0 \to K^+\pi^-) = 0.0389$$

$$\varepsilon_{tag} = \varepsilon_{D^0\to\pi^0\pi^0 \,\&\, \overline{D}^0 \to K^+\pi^-} = 0.005359$$

- We are sitting in the edge of potential achievement
- Other models for $D^0\overline{D}^0$ cross section could be larger than σ_{DD} >100 nb
  e.g. BESIII second solution : σ_{DD} = 486 nb

$$D^0 \to \mu^+ \mu^-$$



Branching fraction

- FCNC decay : $D^0 \rightarrow \mu^+\mu^-$ is further reduced greatly by helicity suppression.

Short distance contribution :

$$BR_{SD}(D^0 \rightarrow \mu^+\mu^-) \sim 10^{-18}$$

Dominated by long distance contribution in particular from $D^0 \rightarrow \gamma\gamma$:

$$BR_{LD}(D^0 \rightarrow \mu^+\mu^-) \sim 2.7\times10^{-5}\, BR(D^0 \rightarrow \gamma\gamma)$$
$$\geq 10^{-13}$$

Theoretical expectation with beyond SM models :

$$BR_{NP}(D^0 \rightarrow \mu^+\mu^-) \sim \text{few} \times 10^{-11}$$

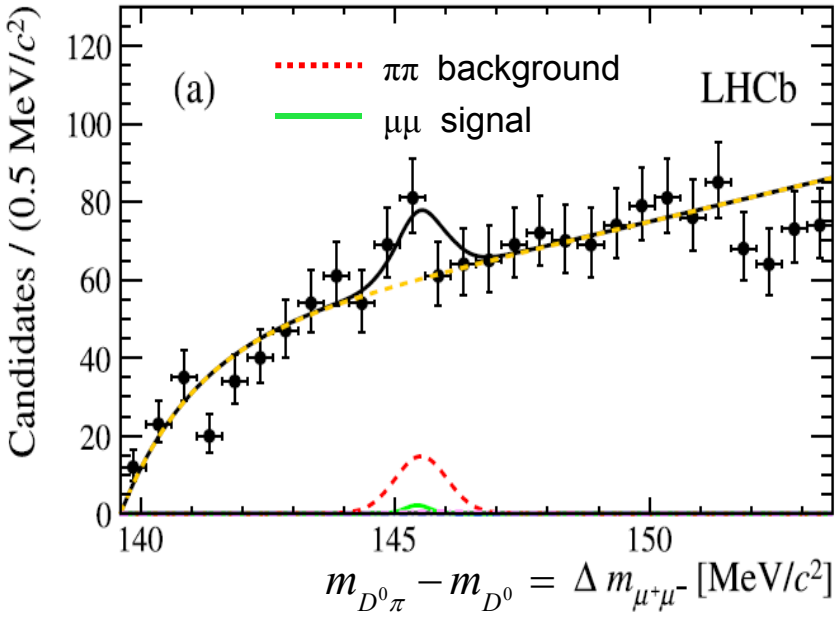
Vectorlike singlet Q=2/3	4×10^{-11}
Vectorlike singlet Q=1/3	$4 \times 10^{-11}(m_s/1\text{TeV})^2$
Z'	$2.4 \times 10^{-12}\ (m_{Z'}\ \text{TeV})^2$
RPV -SUSY	excluded due to constraints $K \rightarrow \pi\nu\bar{\nu}$
Leptoquark (3,1, -4/3)	very suppressed by $\dfrac{D^0 - \bar{D}^0}{(g-2)_\mu}$

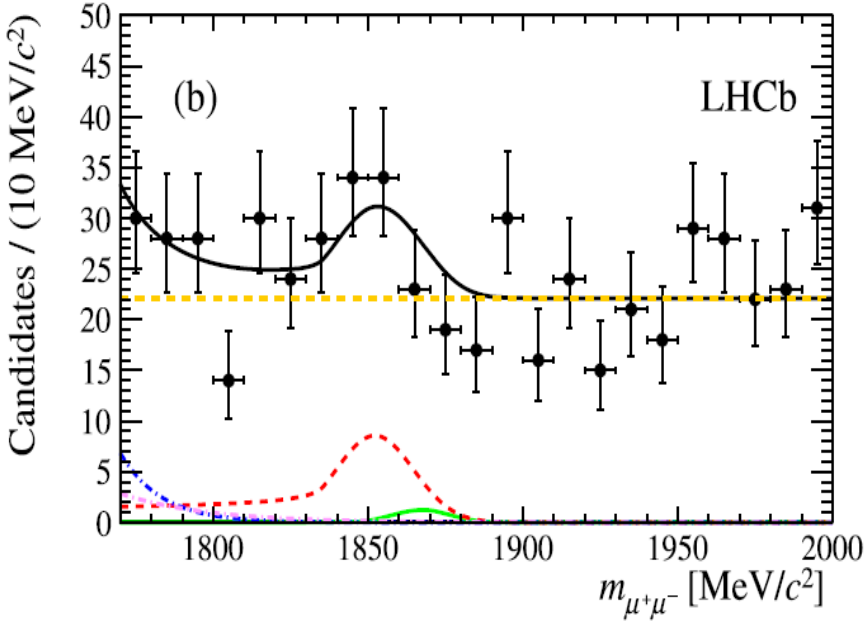
Theory of rare charm decay
S.Fajfer, CHARM 2013

Experimental result

Experimental results (upper limit @ CL=90%)

LHCb(2013)	:	$BR < 6.2 \times 10^{-9}$
PDG(2012)	:	$BR < 1.3 \times 10^{-6}$
CDF,HERA-B	:	$BR < 2.5 \times 10^{-6}$
WA92,E771	:	$BR < 4.1 \times 10^{-6}$





LHCb result [Phys. Letter B 725 (2013) 15]

- pp collision in 7 TeV center of mass energy
- Intergrated luminosity = 0.9 fb^{-1}
- Measured $D^{*+} \rightarrow D^0\pi^+ \rightarrow \mu^+\mu^-\pi^+$
- Upper limit found to be :

$$Br_{D^0 \rightarrow \mu^+\mu^-} < 7.6 \times 10^{-9} \ @\,\mathrm{CL} = 95\%$$

with using $D^0 \rightarrow \pi^+\pi^-$ decay as a normalization

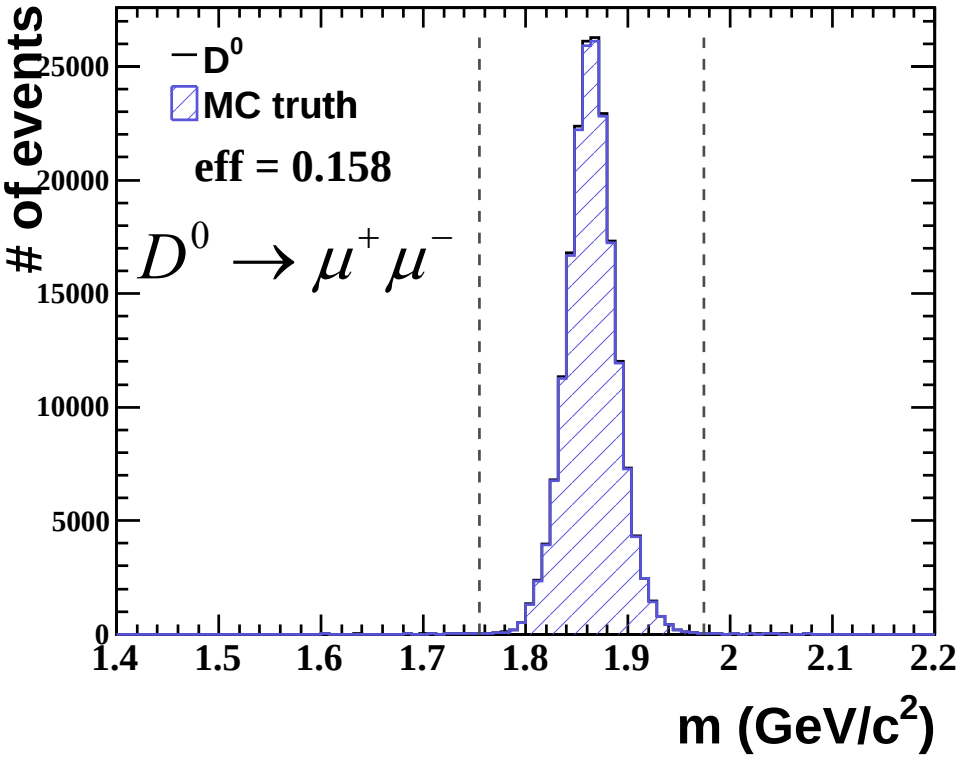
Event selection

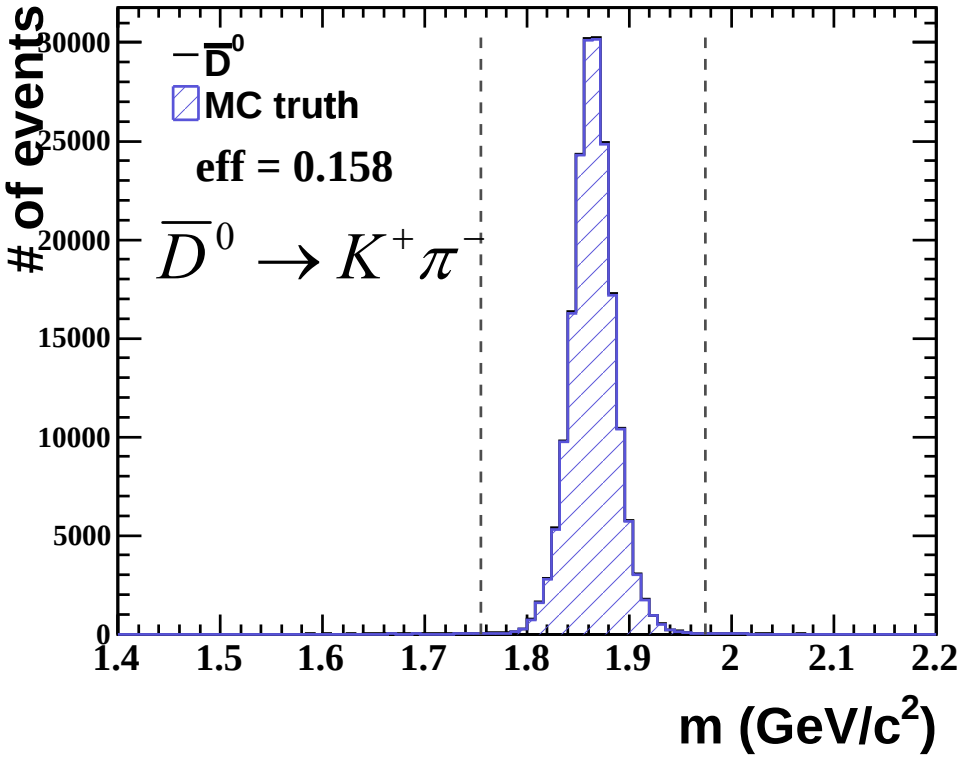
$D^0 \to \mu^+\mu^-$	$\overline{D}^0 \to K^+\pi^-$
$P_t(\mu) > 0.1 GeV/c^2$	$P_t(\pi,K) > 0.1\ GeV/c^2$
$P_t(D) < P_{t,max} + 0.2 GeV/c^2$	$Pt(D) < P_{t,max} + 0.2\ GeV/c^2$
$100° < \Delta\phi_{\mu\mu} < 260°$	$100° < \Delta\phi_{\pi K} < 260°$
PID Prob(μ) > 0.25	PID Prob(π,K) > 0.25
At least 1 muon layer	-
Iron length > 10 cm	-
Mass constrain : $0 < \chi^2 < 10$	Mass constrain : $0 < \chi^2 < 10$

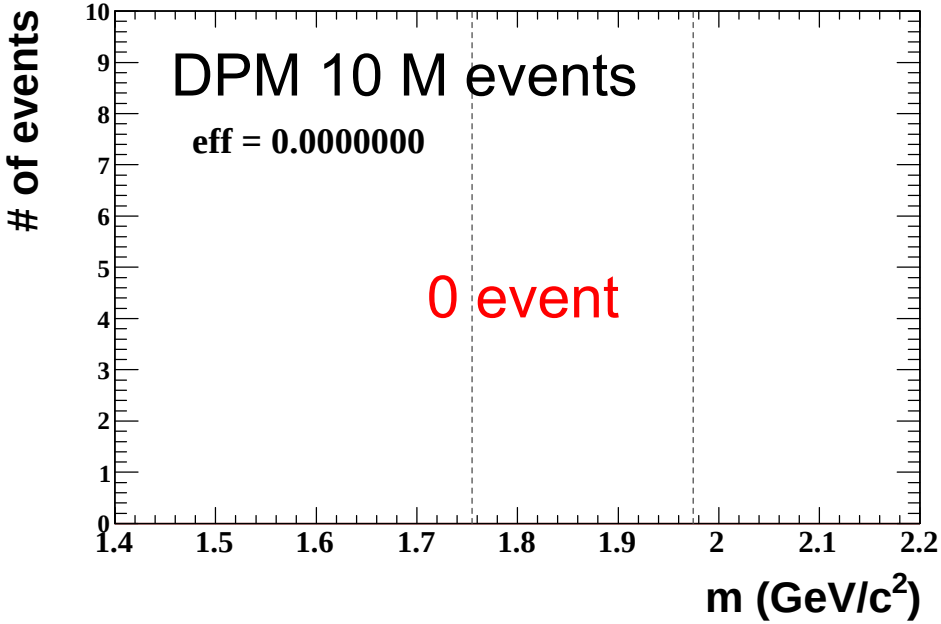
$$D^0\overline{D}^0 \to \mu^+\mu^-\ K^+\pi^-$$

$130° < \Delta\phi_{DD} < 230°$
$-0.99 < \cos\theta CM < 0.99$
Mass constrain : $0 < \chi^2 < 10$

Full simulation







$$\varepsilon = \frac{N_{rec.event,MC}}{N_{gen.event,MC}} \text{ in the histogram}$$

Signal efficiency (double tag)

$$\varepsilon_{tag}^{sig} = 0.158$$

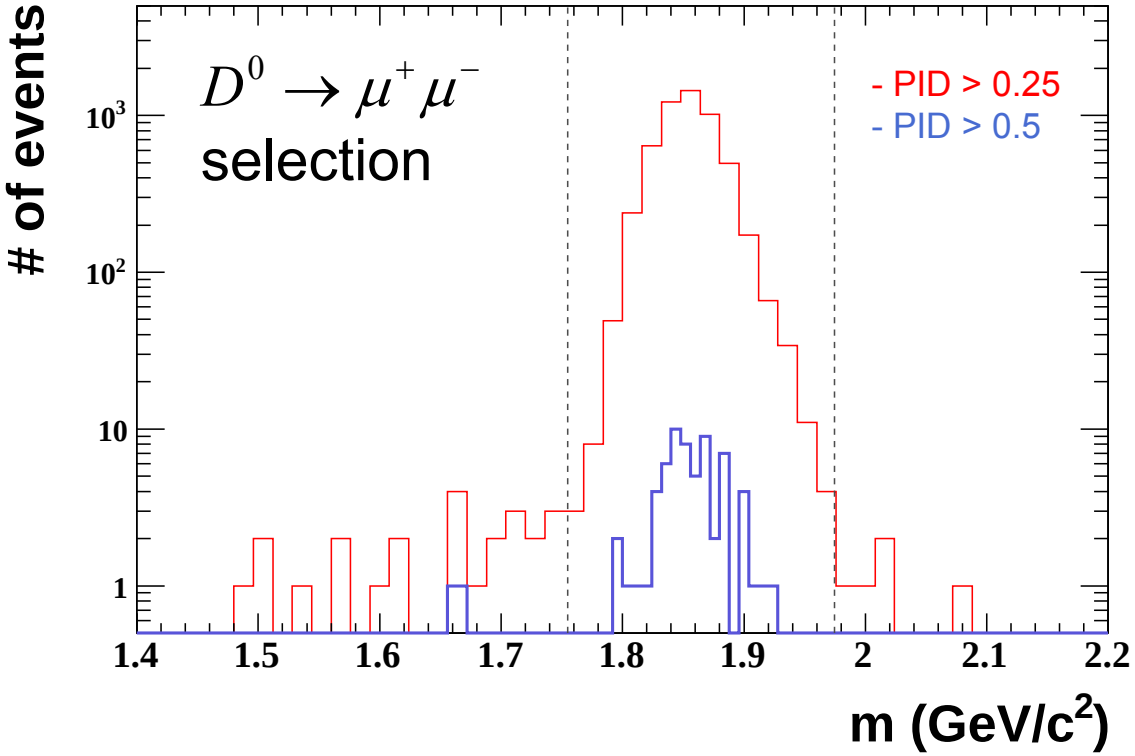
Background efficiency (DPM)

$$\varepsilon_{tag}^{back} < 10^{-7}$$

Background rejection

- Main background source $D^0 \to \pi^+\pi^- (Br = 1.397 \times 10^{-3})$

EvtGen : $\bar{p}p \to D^0\overline{D}^0 \to \pi^+\pi^- \; K^+\pi^-$



All cuts	Signal efficiency	Background reduction
+ PID > 0.25	0.158	0.004535
+ PID > 0.50	**0.113**	**0.000057**

PID tight cut reduce $\pi^+\pi^-$ background effectively

Expected number @ PANDA

$D^0 \to \mu^+\mu^-$ signal data

$$N_{D\to\mu\mu} = 2\,\text{fb}^{-1} \times 100\,\text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$
$$= 0.011\,\text{events}$$

$$Br(D^0 \to \mu^+\mu^-) < 6.2\times10^{-9}\ \text{[LHCb]}$$
$$Br(\overline{D}^0 \to K^+\pi^-) = 0.0389$$
$$\varepsilon_{tag} = \varepsilon_{D^0\to\mu\mu\&\overline{D}^0\to K^+\pi^-} = 0.113$$

$D^0 \to \pi^+\pi^-$ background data

$$N_{D\to\pi^+\pi^-} = 2\,\text{fb}^{-1} \times 100\,\text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$
$$= 1.239\,\text{event}$$

$$Br(D^0 \to \pi^+\pi^-) = 1.397\times10^{-3}\ \text{[PDG(2012)]}$$
$$Br(\overline{D}^0 \to K^+\pi^-) = 0.0389$$
$$\varepsilon_{tag} = \varepsilon_{D^0\to\pi^+\pi^-\&\overline{D}^0\to K^+\pi^-} = 0.000057$$

- With 1.2×10^{11} DPM found **1** background event in the fast simulation

Signal efficiency	Background reduction
0.156	**6.4×10^{-12}**

All cuts + PID > 0.50

- Sensitivity may not be accessible due to very small branching fraction

Summary and Outlook

- $D^0 \to \gamma\gamma$ possible, $D^0 \to \mu^+\mu^-$ difficult @ PANDA
- Not Day-1 experiment, need high luminosity and complete detector setup, assume few years (>3 years) data taking
- Background rejection power 10^{-9} seems to be OK
- Add other decay modes : $\overline{D}^0 \to K^+\pi^-\pi^0 (Br = 13.9\%)$
  π^0 veto should not work due to slow pion
- Different $D^0\overline{D}^0$ decay model in the MC simulation

Backup

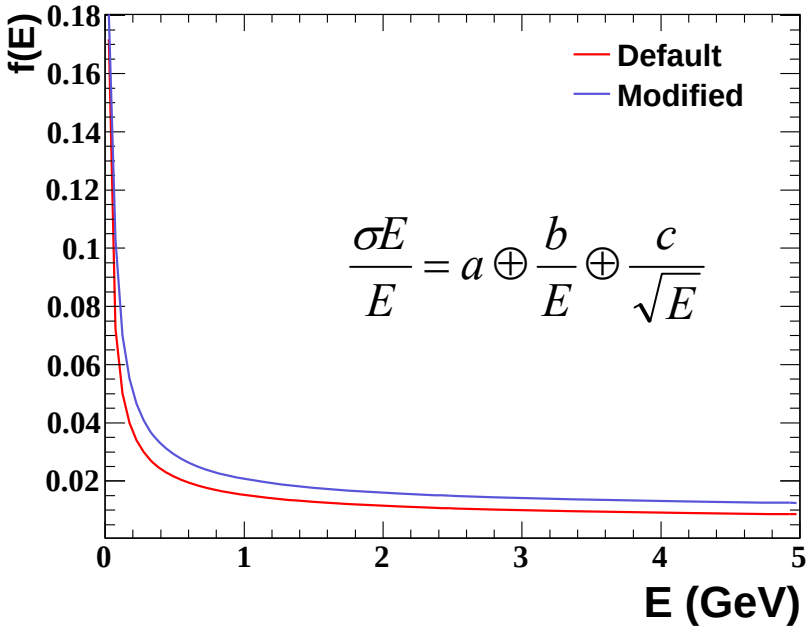
Fast simulation

Tuning of detector parameters @ fast simulation

- Tracking efficiency in barrel part, STT,MVD,GEM
  $\varepsilon=0.85 \rightarrow \varepsilon=0.8$
  Use parameterized efficiency at $P < 0.6$ GeV/c

- PID efficiency in each PID detector : $\varepsilon=1.0 \rightarrow \varepsilon=0.7$
  MDT barrel mis-PID level : $Prob_m=0.01 \rightarrow Prob_m=0.05$

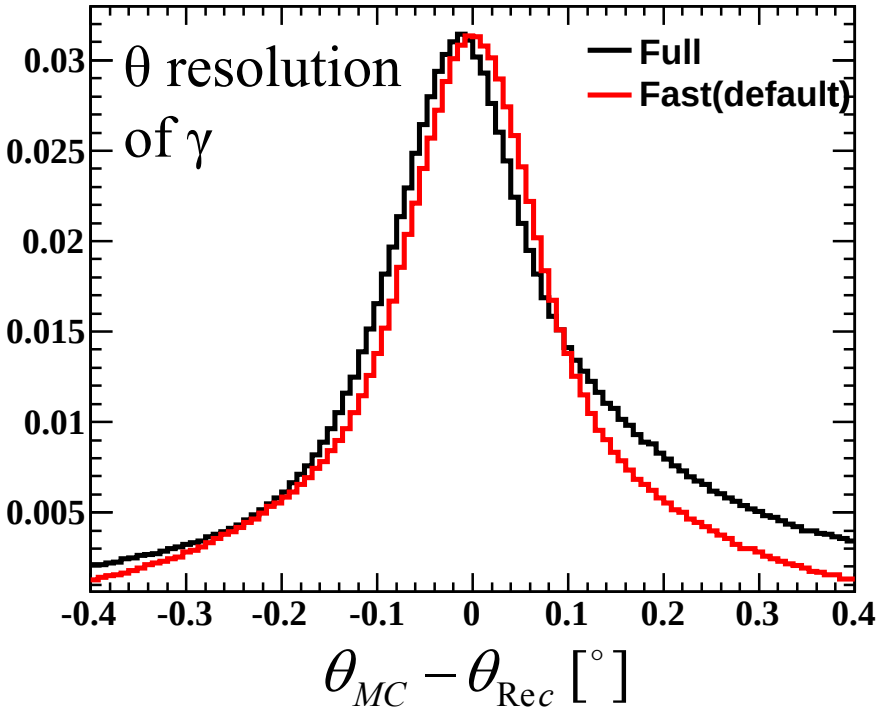
- EMC barrel,endcap,forward efficiency : $\varepsilon=1.0 \rightarrow \varepsilon=0.9$
  Energy resolution for EMC has been tuned

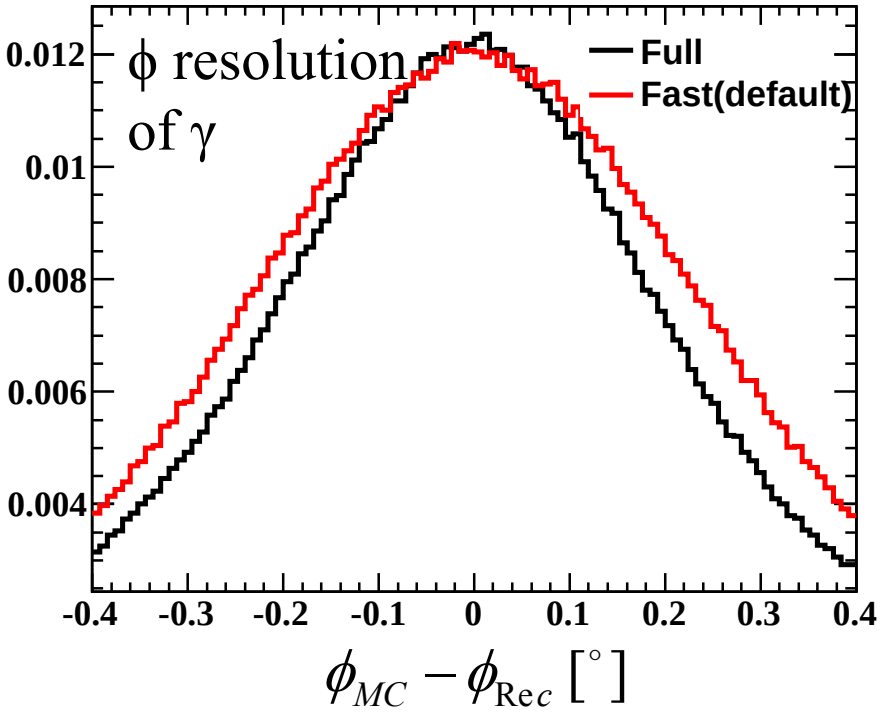


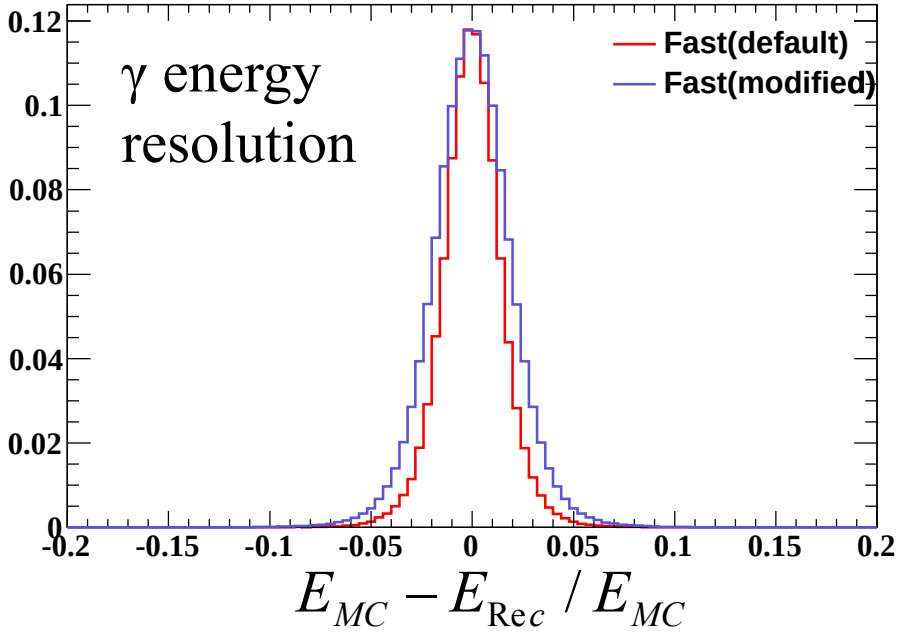
Default	Modified
a= 4.52 × 10^{-3}	a= 8.0 × 10^{-3}
b= 2.95 × 10^{-3}	b= 5.0 × 10^{-3}
c= 7.75 × 10^{-3}	c= 7.75 × 10^{-3}

- shower leakage(a), electric noise(b)

Fast simulation







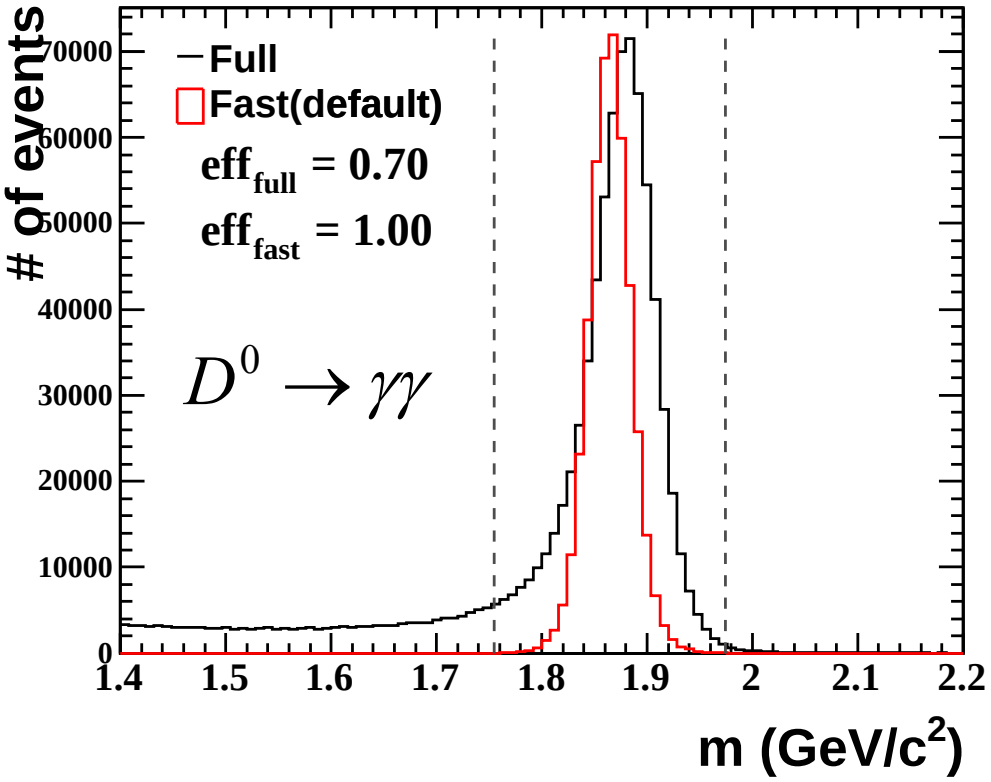
Angular distribution ϕ and θ looks similar between full and fast sim.

Find tuning parameter for energy based on the γ from the data sample

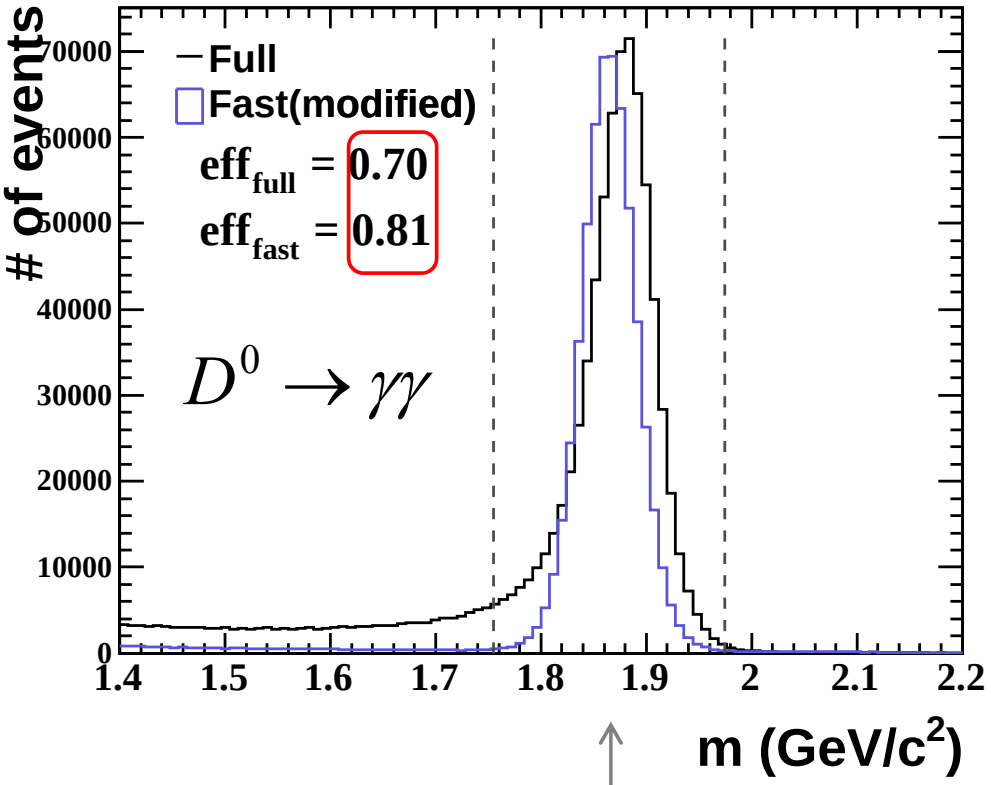
$\pi^0 \to \gamma\gamma$ & $D^0 \to \gamma\gamma$

Fast simulation

Before tuning



After tuning

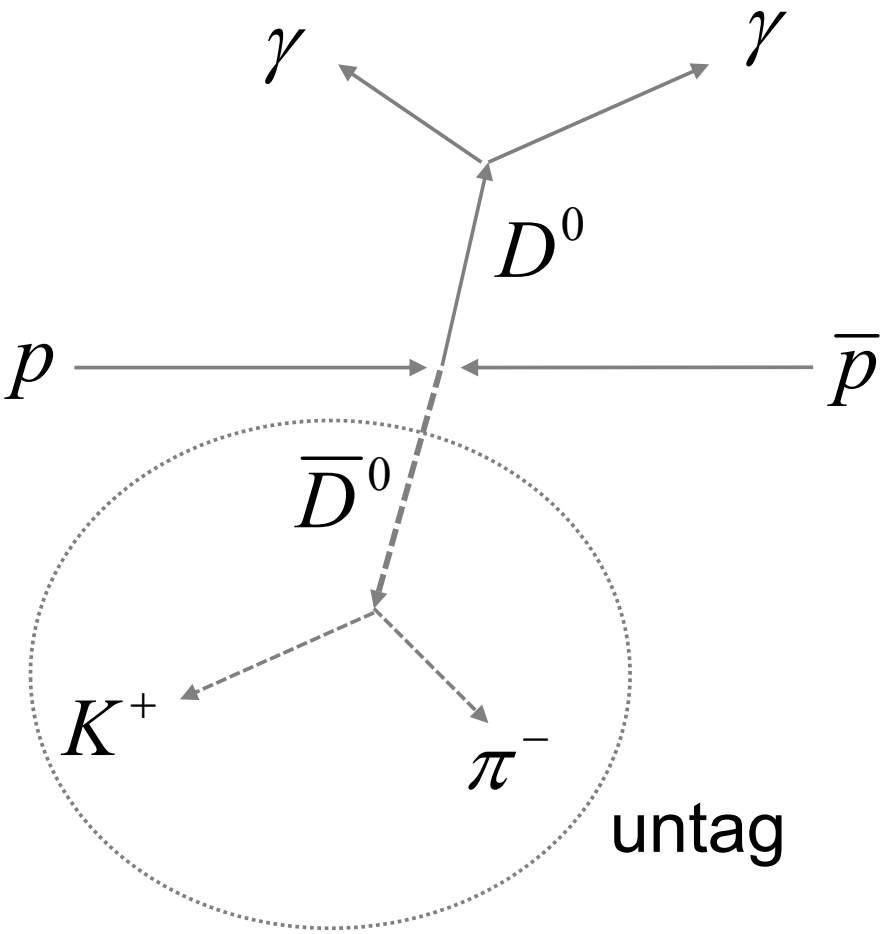


much better balanced distribution for the efficiency and resolution & simulate also radiative tail by activating “split off”

For $\pi^0 \to \gamma\gamma$ mass spectrum show also better agreement with modified parameter

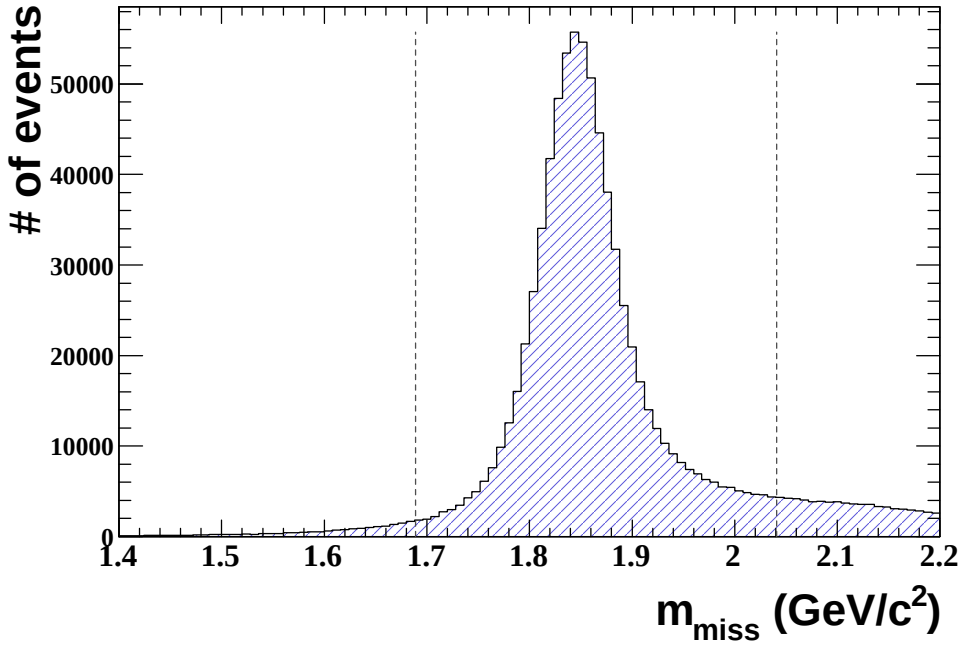
Untag method

Tag-mode will be suffered by additional factor : $Br(\overline{D}^0 \to K^+\pi^-) = (3.89 \pm 0.05)\%$



missing mass of D^0 partner

$$M_{miss} = \sqrt{(E_{CM} - E_{D(\gamma\gamma)})^2 + (\vec{p}_{CM} - \vec{p}_{D(\gamma\gamma)})^2}$$

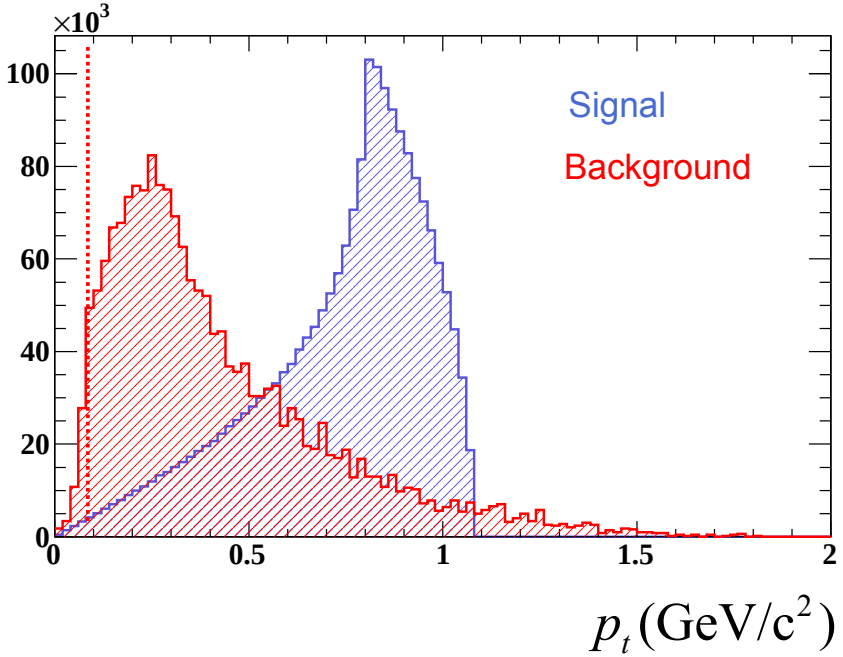


With untag mode, background reduction is not enough

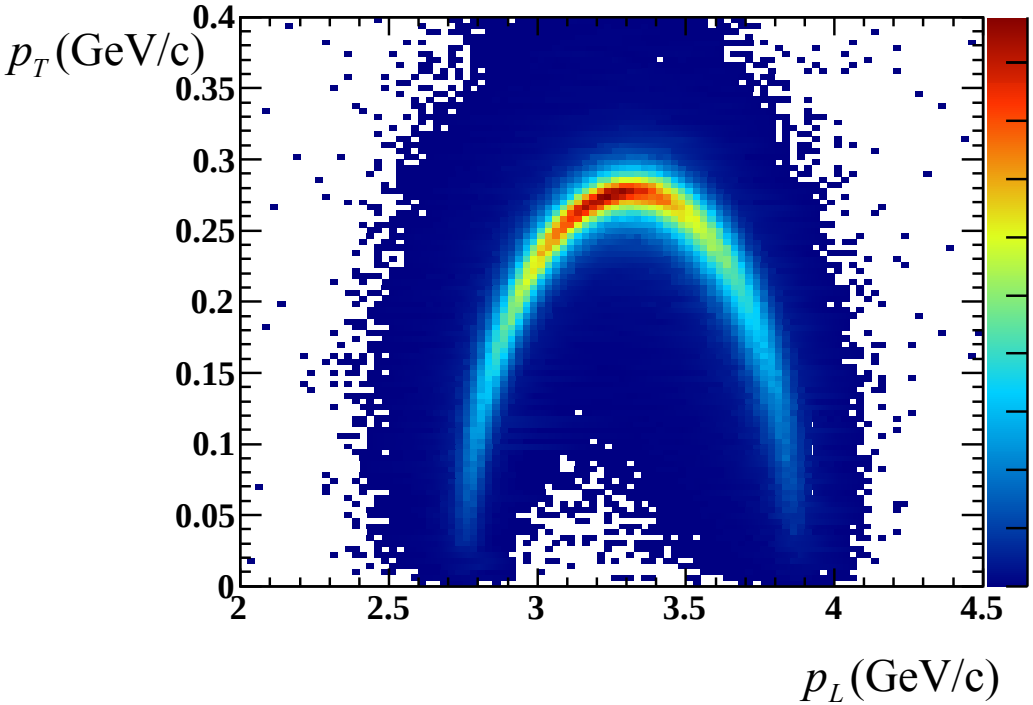
Background rejection

- $p_T > 0.1(\mathrm{GeV/c})$ for γ
- $p_T < p_T^{\max} + 0.2(\mathrm{GeV/c})$ for D^0

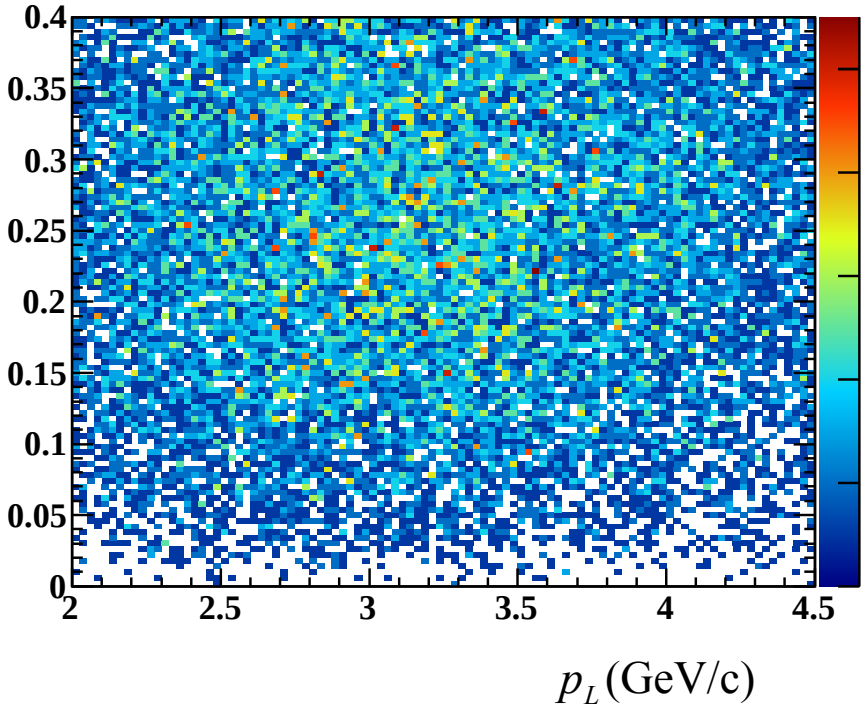
$$p_T^{\max}(\sqrt{s};m) = \frac{\sqrt{s^2 - 4 \cdot s \cdot m^2}}{2\sqrt{s}}$$



Signal



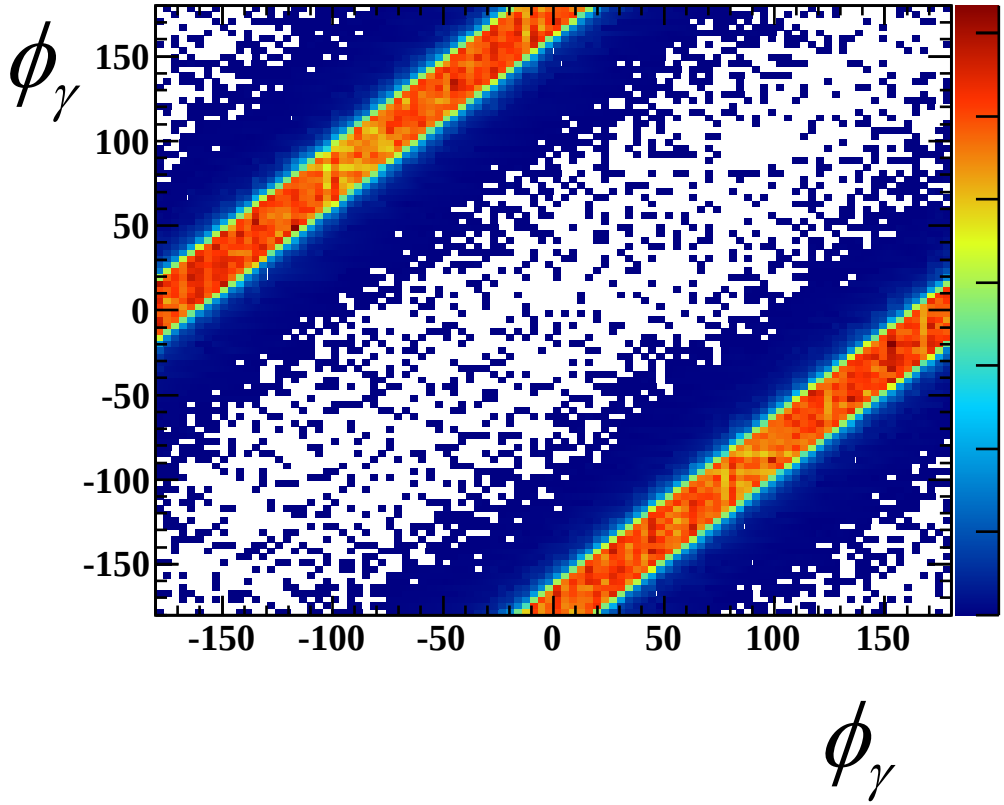
Background



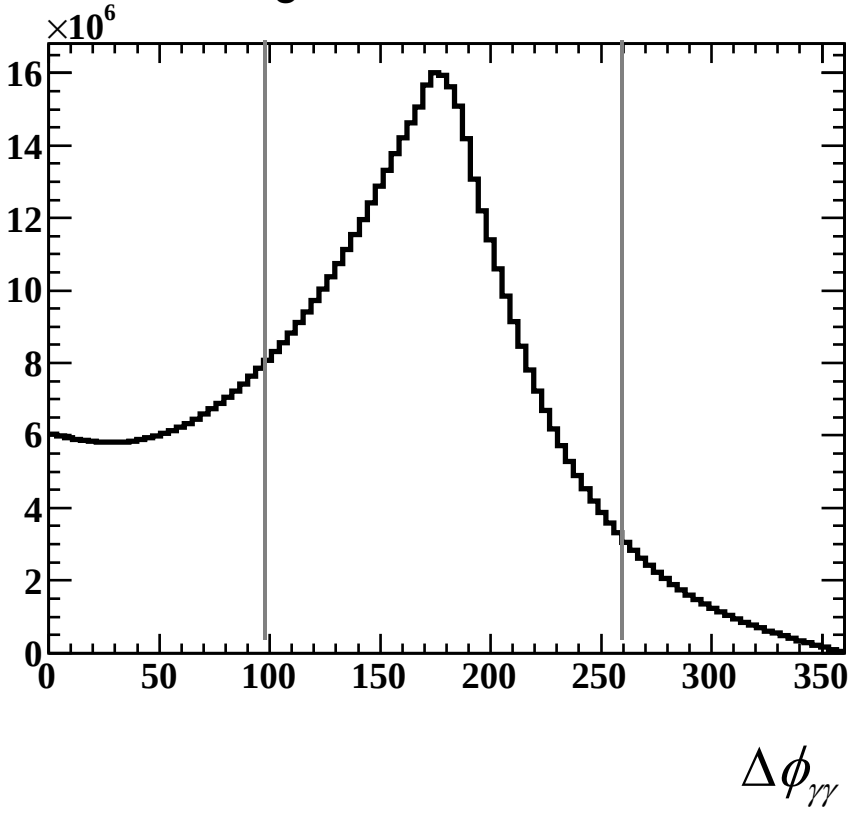
Background rejection

Angular correlation of $\gamma\gamma$

Signal MC generated



Background DPM reconstructed



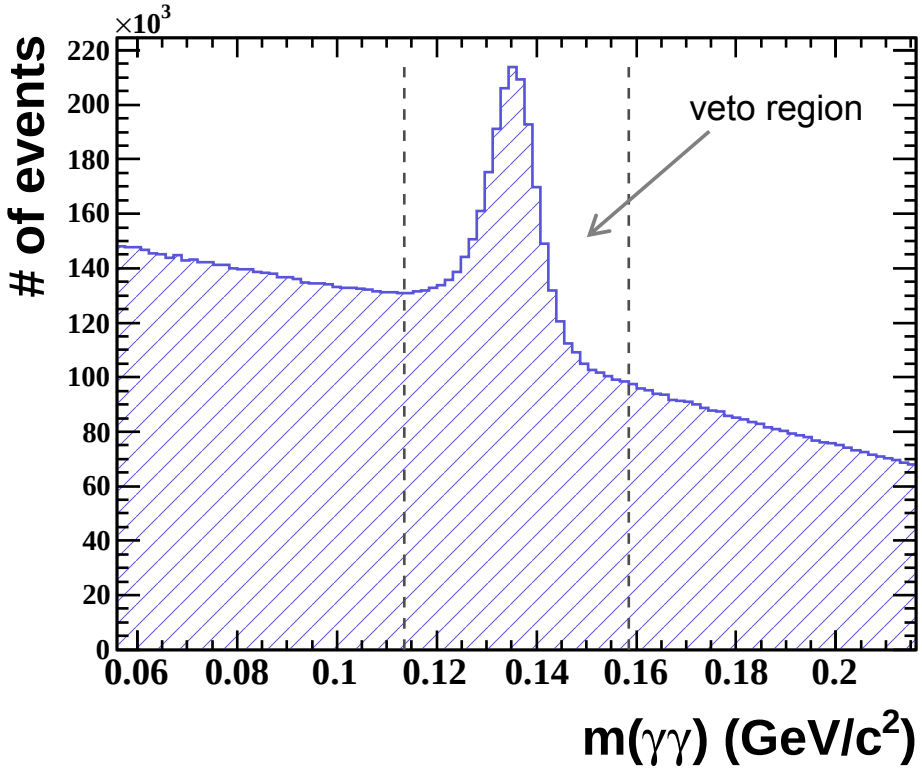
Background rejection

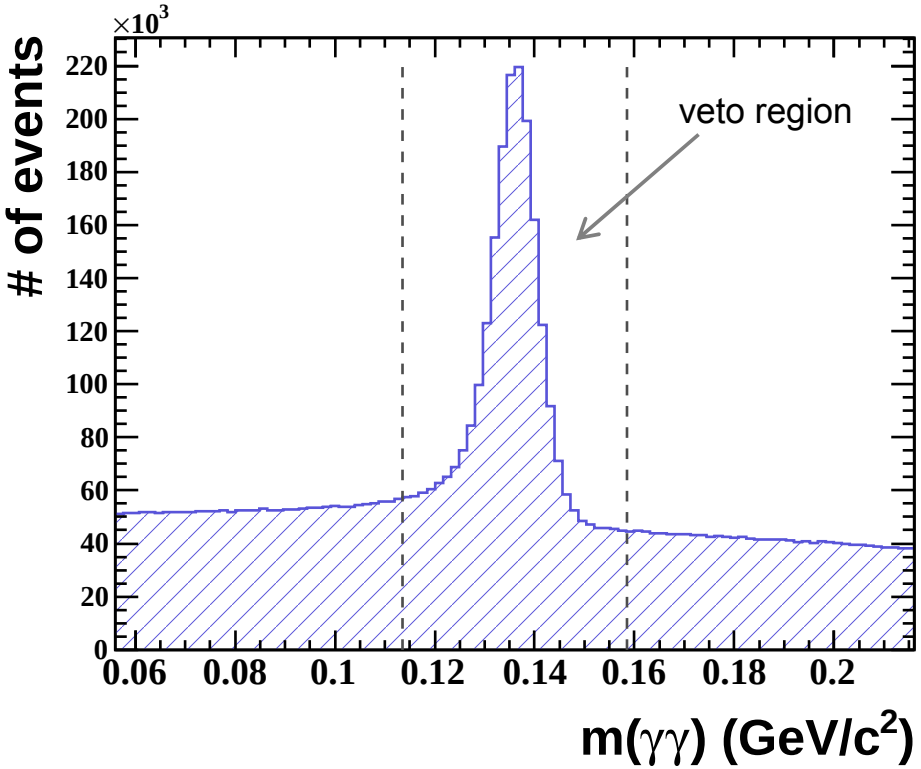
π^0 veto : reject events in which one of the photons can be combined with any other photon candidate in the event to form a π^0

Lower threshold (E= 50 MeV) is more efficient than higher value for π^0 veto

DPM background

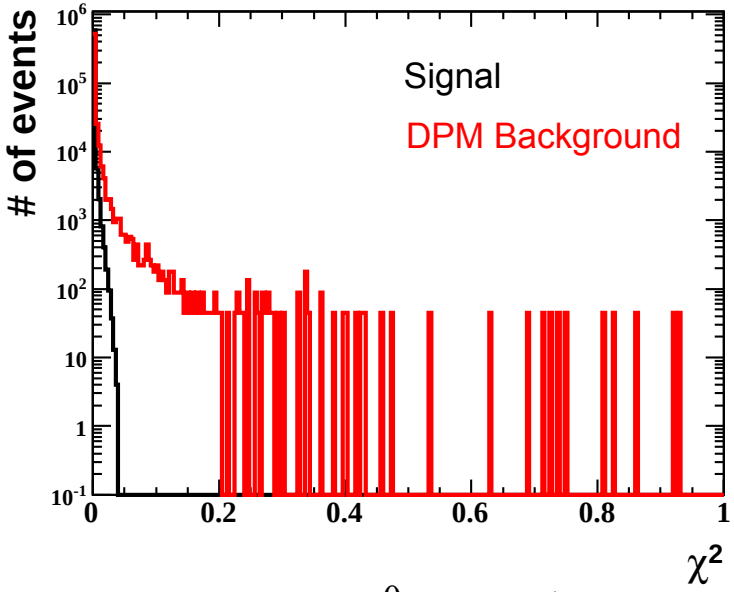
$D^0\overline{D}^0 \to \pi^0\pi^0 K^+\pi^-$

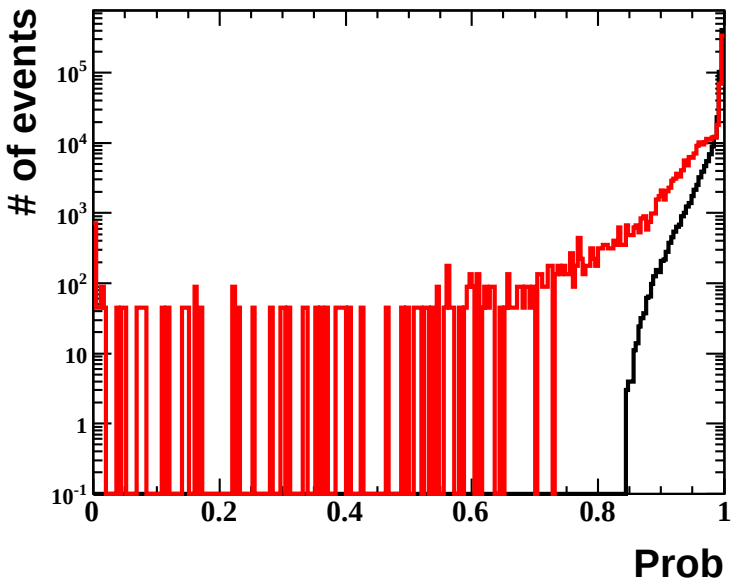




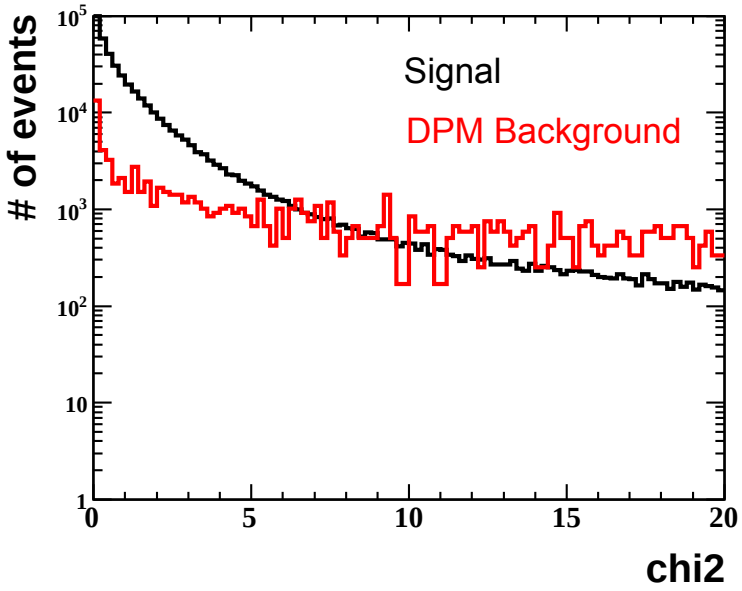
Background rejection

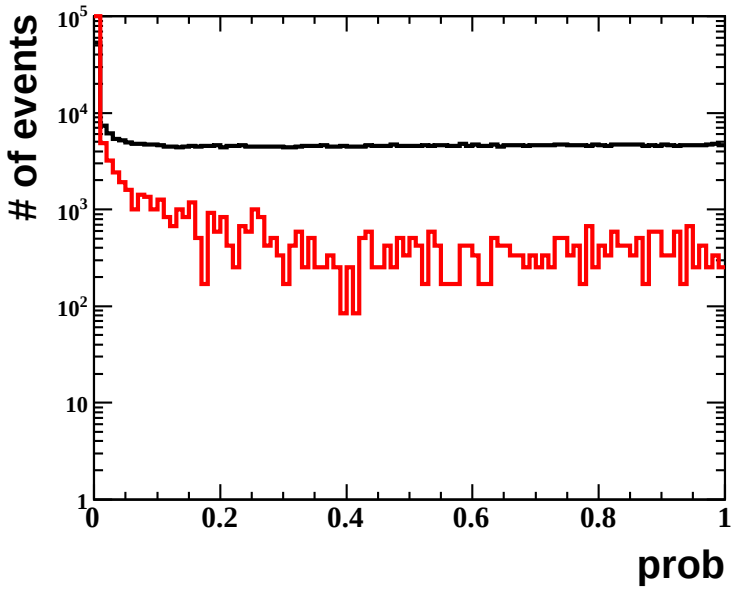
Mass constrain for $D^0 \to \gamma\gamma$





Mass constrain for $D^0 \to \mu^+\mu^-$





Background rejection

Angular correlation of $D^0\overline{D}^0$

$$-0.99 < \cos\theta_{\mathrm{CM,D^0}} < 0.99$$

$$-130^\circ < \Delta\phi_{D^0\overline{D}^0} < 230^\circ$$